EMPIRICAL RELATIONSHIPS OF THE CENTRAL PRESSURES IN HURRICANES TO THE MAXIMUM SURGE AND STORM TIDE

ROBERT A. HOOVER

U. S. Weather Bureau Forecast Center, Washington National Airport, Washington, D. C.

[Manuscript received May 10, 1957; revised July 8, 1957]

ABSTRACT

Surge and storm tide profiles are constructed to determine the maximum surge and storm tide heights of hurricanes and tropical storms for which sufficient tide data are available. In cases where less tide data are obtainable, interpolated and extrapolated profiles are used to estimate the maximum heights. The relation of these heights to the central pressures of the storms is shown.

1. INTRODUCTION

Often the most destructive part of a hurricane is the hurricane surge, or the rapid rise in sea level which accompanies the storm as it moves inland. Investigators have suggested many variables which may affect the height of this surge. To mention a few, we would speak of such parameters as the intensity, size, speed, and path of the storm; the general configuration of the coastline; bottom topography near the coast; and the stage of the astronomical tide. There are probably other large-scale features which affect the height of the surge, and in addition, there are many small-scale features which may, in many cases, greatly modify the surge height locally, such as convergence or divergence in bays and estuaries, local wind-setup, seiching, etc. An attempt is made in this study to develop a forecasting tool which embodies some of the broadscale features and minimizes the local effects.

A moderately large number of tide observations is available for a few hurricanes, but for the majority of the storms there are only a few good observations and often none within the zone of hurricane winds. Conner, Kraft, and Harris [1] have recently published a paper in which the highest observed storm tide along the open coast is related to the lowest central pressure in the storm. This procedure is biased in the direction of underestimating the maximum tide height, for the highest actual tide may frequently go unobserved. This is especially true when no observations are obtained near the center of the storm.

There is some hope of correcting this defect and increasing the number of storms used in the formation of the prediction equation by constructing standard tide profiles which could be used for estimating the maximum storm tide from the observed high tides of a large number of storms. This procedure involves the acceptance of certain assumptions, which further study may show to be unjustified, but in view of the limited amount of first class data available at the present time, and the importance of the problem, this procedure is believed to be justified if not actually required. A considerable amount of subjectivity is required in the construction of the profiles, and another analyst might differ on many of the details, but the close agreement between the results of this study and that by Conner, Kraft, and Harris, which was conducted concurrently, implies that the differences should not be significant in a statistical sense.

2. INDIVIDUAL TIDE PROFILES

An examination of the surge profiles constructed by such investigators as Redfield and Miller [2], Hubert and Clark [3] and the writer, shows the profiles to be "bell shaped". In general, the peaks have been found to be near or to the right of the point where the hurricane enters the coastline. Barring some abnormality in the coastline, it is logical to believe that there is one place where the surge is higher than at surrounding points and that the surge height decreases with distance from this point. With this in mind, surge profiles have been drawn of cases for which sufficient tide data were available.

Figure 1 contains examples of two tide profiles (see appendix for balance of the profiles used in this study). These two profiles are neither the poorest nor the best documented ones used in the study; they are presented to show the manner in which they are drawn and the subjectivity involved.

The basic assumption in studies of this type is that the storm surge, that is, the difference between the actual elevation of the sea surface and the elevation which would have existed in the absence of a storm, is strongly related to the minimum atmospheric pressure in the storm. A continuous record of the water elevation and a continuous prediction of the normal tide are obviously necessary to permit an accurate determination of the storm surge. Data of this type have been used where available, and are indicated by solid circles on the profile charts. However, many good observations of the maximum tide

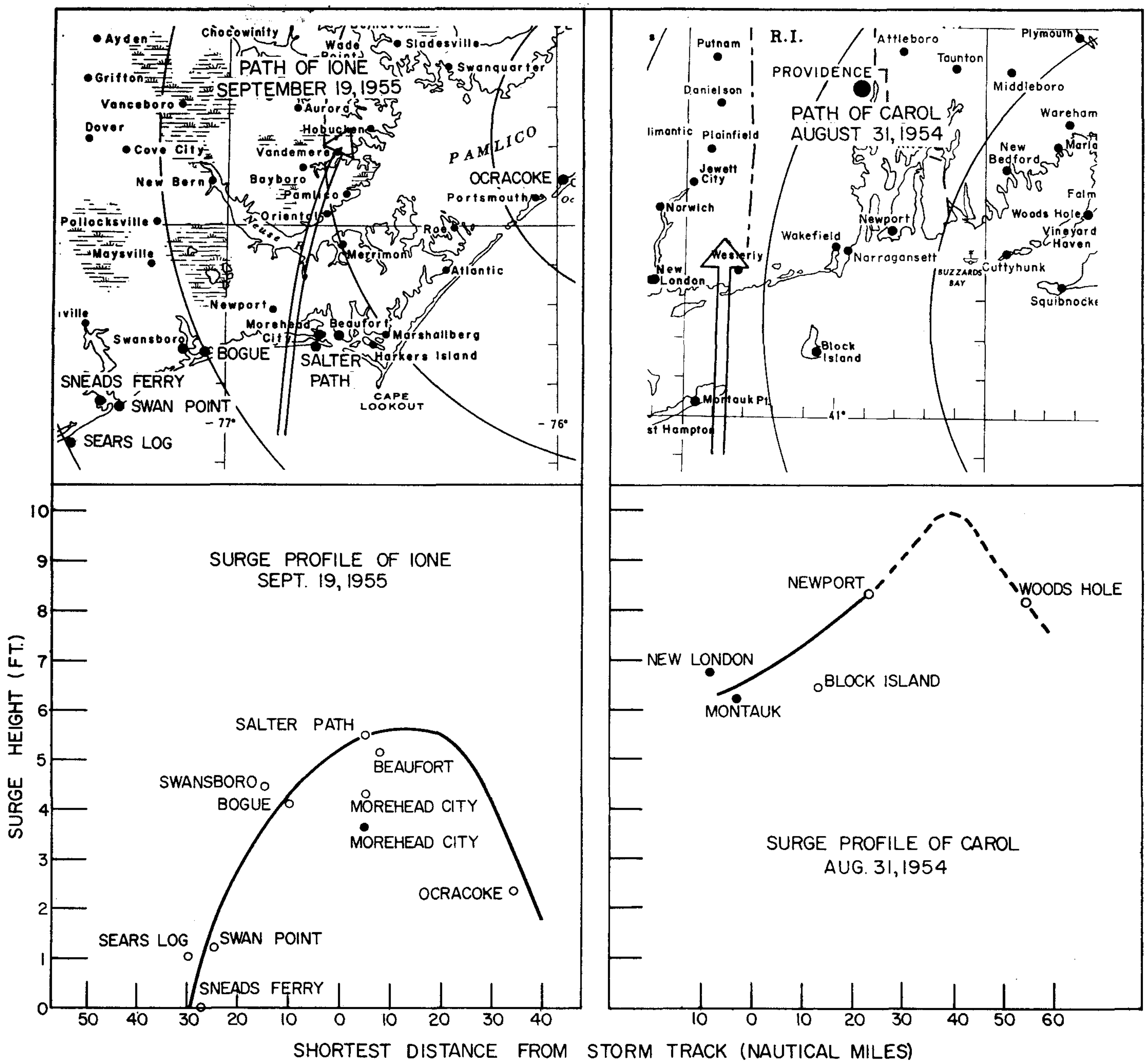

FIGURE 1.—Surge profiles of hurricanes Ione, September 19, 1955 and Carol, August 31, 1954. Open circles indicate discontinuous-type data.

height are obtained from locations which do not have recording tide gages, and in some cases the recording tide gages have failed before the highest tide elevations were reached. In such cases the maximum height of the observed tide and its time of occurrence may be known, and a good estimation of the stage of the astronomical tide at this time may be available, yet this is not sufficient for an accurate determination of the maximum storm surge unless the highest meteorologic tide coincides with the time of predicted high tide. The reason for this can be readily seen by reference to figure 2 which shows the observed, predicted, and meteorologic tides at the Little Creek gage, Norfolk, Va., for hurricane Connie. Note that the maximum observed tide occurred near the time of a predicted high tide and yielded a surge value of 2.3 feet, while the maximum surge of 4.2 feet occurred near the time of predicted low tide. Due to the very limited amount of ideal data for this study, data of the discontinuous type must be used and have been indicated on the figures by open circles. In these instances an estimate of the stage of the astronomical tide was made and removed from the observed tide by assuming the maximum surge height to have occurred near the time the storm entered the coast.

Most of the continuously recorded water level data used in this study have been obtained from the U. S.

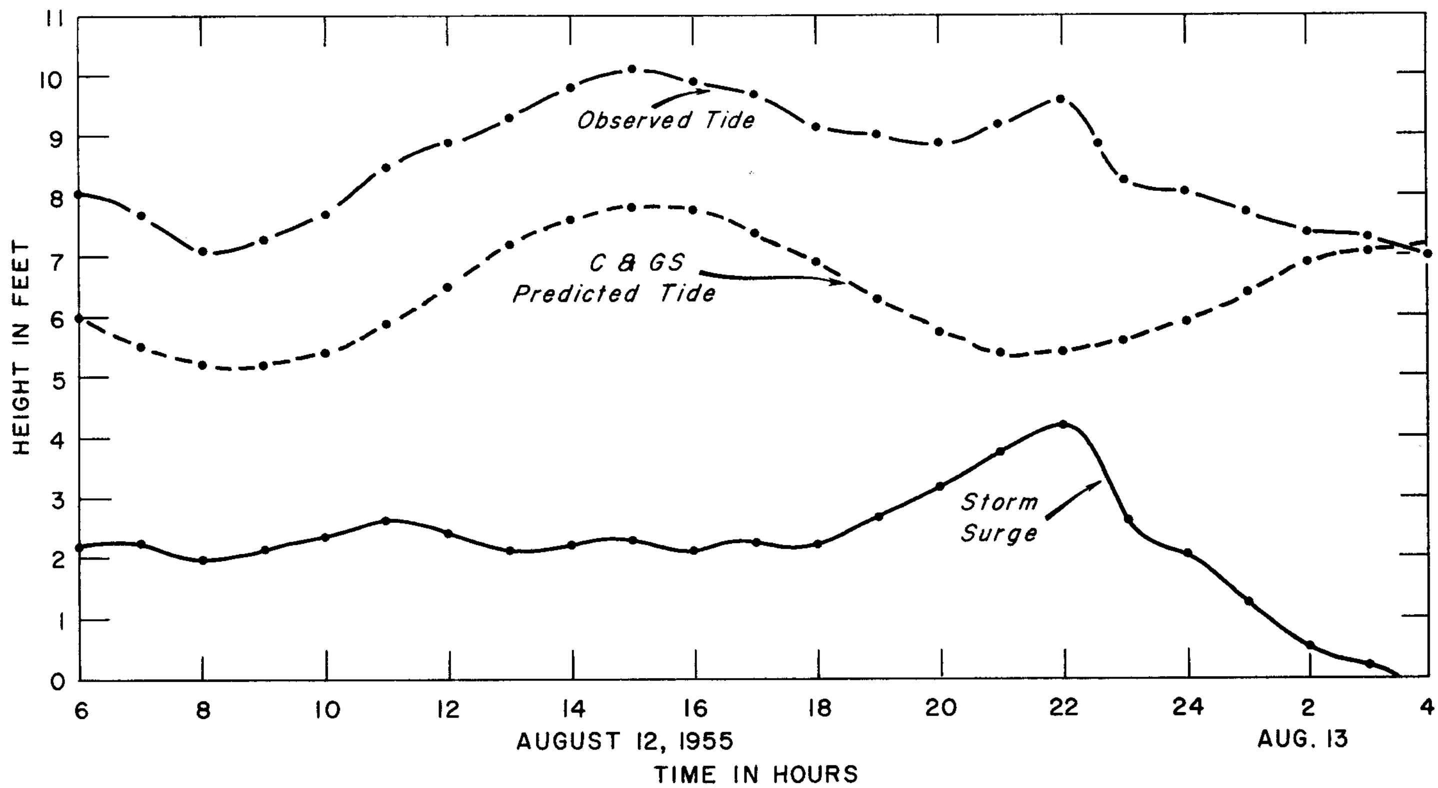

FIGURE 2.—Observed, predicted, and meteorologic tides at Little Creek, Norfolk, Va., for hurricane Connie, August 1955.

Coast and Geodetic Survey. Local observations of maximum tide height have been obtained from many sources, but most of the data not previously published have been furnished by the District Offices of the U. S. Army Corps of Engineers.

The profiles were drawn by inspection with some consideration being given to how nearly the observations were believed to represent open coast conditions. For example, in the case of Ione, shown in figure 1, the two Morehead City values were given less weight than the Salter Path value which was believed to be more representative.

In the case of Carol, the data for Newport and Woods Hole, although obtained from tide gage locations, are shown as open circles because both these gages became inoperative before the highest water levels were reached in this storm. The Coast and Geodetic Survey observations are more or less drawn for, while the estimated value at Block Island is given less weight. Tide observations for other hurricanes at Block Island have been found to be lower than those along the southern New England coast. Perhaps this is because the surge has the opportunity to pass by Block Island, while the southern coast of New England forms more of a barrier. The peak is shown as 10 feet, but, admittedly in this case, the profile could have been drawn to show a peak anywhere between 9 and 11 feet.

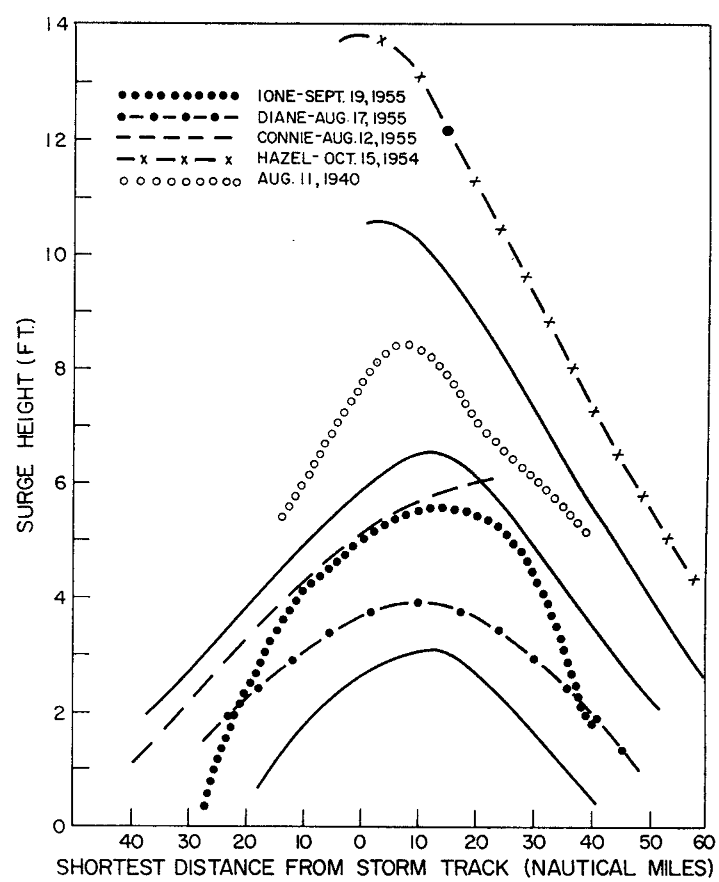

FIGURE 3.—Surge profiles of the hurricanes which entered the coasts of North Carolina, South Carolina, and Georgia.

3. INTERPOLATED PROFILES

It was found that tide profiles for certain coastlines resemble one another more than those for other coastlines.

TABLE 1.—*Data for Atlantic coast hurricanes*

Reference No. and date of hurricane	Approximate coastline of entry	Maximum observed tide height above normal (feet)	Location	Minimum distance from track (N. mi.)	Central pressure (mb.)	Estimated maximum surge (ft.)
1. Ione, Sept. 19, 1955	Morehead City, N. C		(Individual profile used)		966	5.7
2. Diane, Aug. 17, 1955	Cape Fear, N. C		do		987	3.9
3. Connie, Aug. 12, 1955	Beaufort Inlet, N. C		do		968	6.0
4. Hazel, Oct. 15, 1954	N. C.-S. C. State Line		do		937	13.8
5. Carol, Aug. 31, 1954	Stonington, Conn		do		962	9.9
6. Barbara, Aug. 13, 1953	Wildwood, N. C	1.5	Morehead City, N. C	10 miles to left	*989	2.4
7. Aug. 30, 1952	Beaufort, S. C	3.2	Charleston, S. C	40 miles to right	983	5.5
8. Oct. 15, 1947	Ossabaw Sound, Ga	8.5	Savannah, Ga	10 miles to right	968	8.7
9. Oct. 19, 1944	Charleston, S. C	4.3	Charleston, S. C	Near track	*980	5.0
10. Sept. 14, 1944	Point Judith, R. I		(Individual profile used)		959	8.9
11. Aug. 11, 1940	Savannah, Ga		do		975	8.3
12. Sept. 21, 1938	New Haven, Conn		do		948	11.6
13. Aug. 23, 1933	Oregon Inlet, N. C	6.7	Norfolk, Va	10 miles to right	970	6.9
14. Sept. 18, 1928	Charleston, S. C	3.8	Charleston, S. C	Near track	*979	4.2
15. Aug. 28, 1911	Hilton Head, S. C	5.6	do	30 miles to right	979	8.0
16. Sept. 17, 1906	Cedar Island, S. C	1.5	do	30 miles to left	981	3.0
17. Oct. 13, 1893	Winyah Bay, S. C	8.3	Winyah Bay, S. C	Near track	959	8.6
18. Aug. 28, 1893	Savannah, Ga	15.3	Fort Pulaski, Ga	do	*950	15.5

*Not obtained from [4].

For example, the surge peaks for the New England hurricanes seem to be displaced farther to the right of the hurricane track than those for North Carolina, South Carolina, and Georgia. Figure 1 is an example of this difference. Because of this difference, the profiles for the New England hurricanes were not included in figure 3 which contains the profiles for hurricanes entering the coasts of North Carolina, South Carolina, and Georgia. The solid lines are interpolated and extrapolated profiles drawn by inspection and were inserted as guides to be used for estimating the maximum surge heights for other hurricanes. For example, if there was a single surge value of 5 feet at 30 nautical miles to the right of a hurricane track in this region, the maximum height would be estimated as about 7 feet.

As would be expected, the accuracy of such a chart decreases as the distance from the center increases. For this reason the profiles were not used beyond about 50 nautical miles to the right and 40 nautical miles to the left of the hurricane track.

4. REGRESSION LINE FOR ATLANTIC HURRICANES

Table 1 contains a list of all the hurricanes entering the Atlantic coast north of Jacksonville for which central pressures and tide data could be found. The approximate coastline of entry was obtained from *Hydrometeorological Report No. 32* [4] when possible. Otherwise entry points were obtained from the *Monthly Weather Review* and individual analyses. Central pressures were obtained from *Hydrometeorological Report No. 32* except for those marked with an asterisk.

Figure 4 shows the regression of maximum surge height on central pressure for the Atlantic storms. The circled numbers indicate heights obtained from the individual tide profiles, while the uncircled ones were estimated from the interpolated and extrapolated profiles.

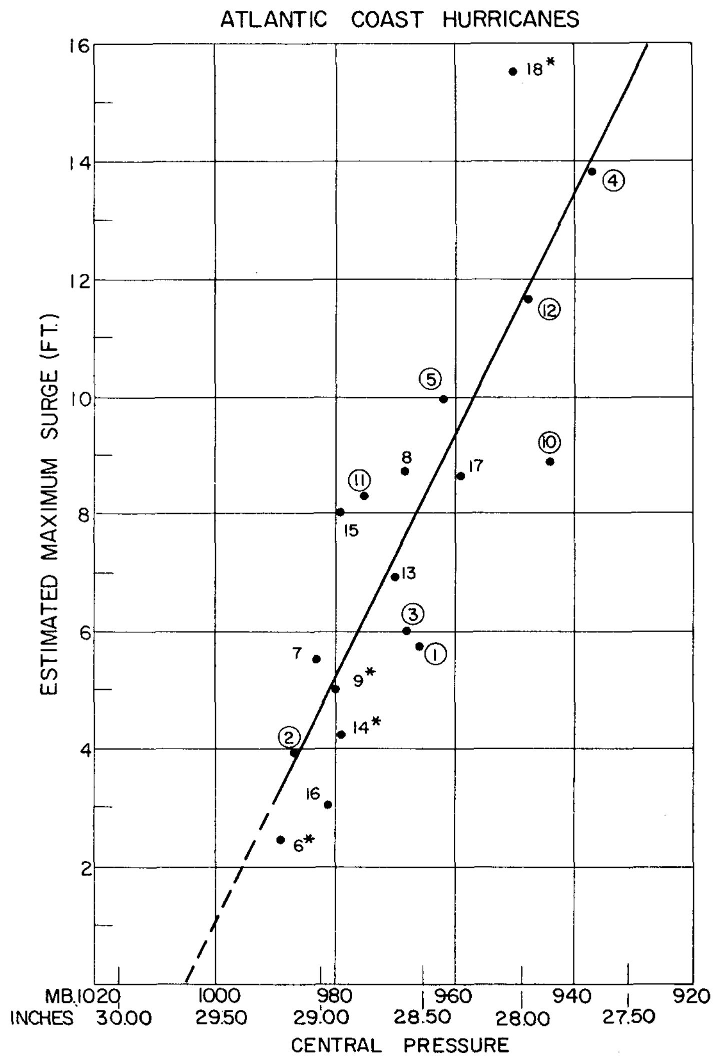

FIGURE 4.—Regression of maximum surge height on central pressure for hurricanes entering the United States Atlantic coastline north of Jacksonville, Fla. Plotted numbers correspond to storm numbers in table 1; those circled are obtained from individual tide profiles, others are extrapolated or interpolated. Asterisk indicates central pressure not obtained from [4]. NOTE: Point 10 is misplotted; it should be at a pressure of 959 mb.

5. GULF OF MEXICO HURRICANES

Because most of the available tide values for the Gulf

TABLE 2.—*Data for Gulf of Mexico hurricanes*

Reference No. and date of hurricane	Approximate coast line of entry	Maximum observed tide height above MSL (ft.)	Location	Minimum distance from track (N. mi.)	Central pressure (mb.)	Interpolated profiles used	Estimated maximum storm tide (ft.)
1. Aug. 30, 1950	Orange Beach, Ala	5.5	Pensacola, Fla	15 to right	979	South	5.8
2. Oct. 4, 1949	Cedar Lake, Tex		(Individual profile used)		978		10.4
3. Sept. 4, 1948	Grand Island, La	5.6	Biloxi, Miss	45 to right	*987	South	10.0
4. Sept. 19, 1947	New Orleans, La		(Individual profile used)		968		13.0
5. Aug. 27, 1945	Matagorda Island, Tex		do		968		8.7
6. July 27, 1943	Port Bolivar, Tex	4.0	Galveston, Tex	10 to left	975	Southeast	10.0
7. Aug. 30, 1942	Seadrift, Tex		(Individual profile used)		951		14.0
8. Oct. 7, 1941	Harbeson City, Fla	8.0	St. Marks, Fla	25 to right	981	Southeast	8.0
9. Sept. 23, 1941	5 miles SW Sargent, Tex	9.9	Sargent, Tex	5 to right	959	do	12.3
10. Aug. 7, 1940	Texas Point, La	4.8	Calcasieu Pass, La	20 to right	974	do	5.0
11. July 31, 1936	Destin, Fla	6.0	Panama City, Fla	40 to right	964	do	7.0
12. Sept. 5, 1933	Brownsville, Tex	13.0	Brownsville, Tex	Near track	949	do	14.8
13. Sept. 20, 1926	Perdido Bay, Ala	7.6	Pensacola, Fla	7 to right	956	do	11.4
14. Aug. 25, 1926	Lake Pelt, La	10.0	Timbalier Bay, La	30 to right	959	do	10.3
15. Sept. 14, 1919	Chapman Ranch, Tex	11.1	Port Aransas, Tex	30 to right	948	do	11.3
16. Sept. 28, 1917	Horosa, Fla	7.1	Fort Barrancas, Fla	10 to left	964	South	9.6
17. July 5, 1916	Pascagoula, Miss		(Individual profile used)		961		8.1
18. Sept. 29, 1915	Timbalier Pass, La		do		944		11.2
19. Aug. 16, 1915	Freeport, Tex		do		953		14.8
20. Sept. 13, 1912	Cedar Point, La	4.4	Mobile, Ala	15 to right	*993	Southeast	5.0
21. July 21, 1909	4 miles SW Freeport, Tex	10.0	Galveston, Tex	35 to right	959	do	10.8
22. Aug. 14, 1901	Biloxi, Miss	7.4	Mobile, Ala	22 to right	973	South	9.0
23. Sept. 8, 1900	6 miles NE Freeport, Tex	14.5	Galveston, Tex	25 to right	936	Southeast	15.0
24. Oct. 2, 1893	Mobile, Ala	8.4	Mobile, Ala	Near track	956	South	12.3

*Not obtained from [4].

coast were above the mean sea level datum and the range of the astronomical tide is small, no adjustment was made for the stage of the astronomical tide. The tide heights in these cases are not true surge heights and will for this reason be referred to as storm tide heights.

In this portion of the study extensive use was made of the profiles constructed by Hubert and Clark [3]. Some were used as they were drawn, while in other cases where new data and information were found, slight changes were made. Tide data supplied by Mr. James Taylor of Galveston was also used in the construction of these profiles. The same type of tide report designation used by Hubert and Clark was followed.

An examination of the individual profiles for the Gulf hurricanes seemed to indicate that profiles of hurricanes which entered the coastline from the east-southeast and southeast were broader than those entering the coastline from the south-southeast, south, or south-southwest. For this reason best results were obtained by dividing the profiles into these two groups. Interpolated and extrapolated profiles were drawn in the same fashion as those for the Atlantic coast. (See appendix for the Gulf coast profiles.)

The Florida Peninsula was not included in this study because it was felt that a separate set of profiles would be needed, and only one profile for each side of the Peninsula was available.

Table 2 contains a list of all the Gulf coast storms used in this study. All of the data contained in the column Maximum Observed Tide Height were obtained from Conner, Kraft, and Harris [1]. Four cases included in their paper were omitted because the tide observations were considered to be too distant from the storm track. These were the hurricanes of September 27, 1906, September 20, 1909, July 25, 1934, and August 24, 1947. In addition, storms entering the Florida Peninsula were not included for the reasons given above. These were the hurricanes of October 25, 1921 and September 5, 1950.

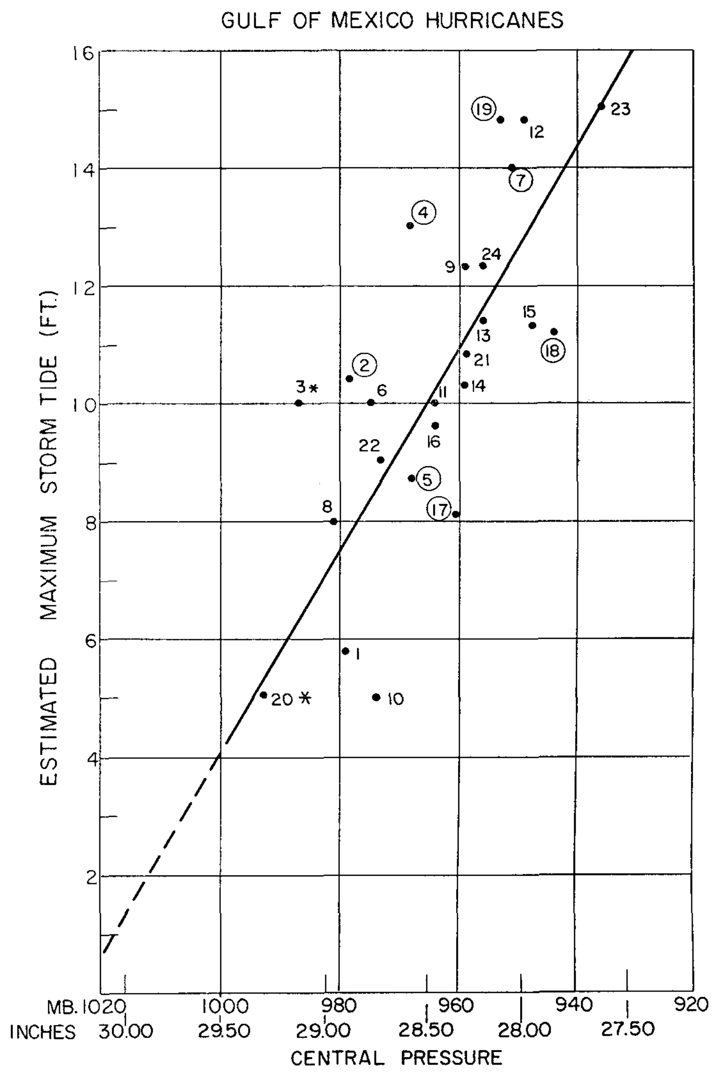

FIGURE 5.—Regression of maximum storm tide height on central pressure for hurricanes entering the United States Gulf of Mexico coastline west of Tallahassee, Fla.

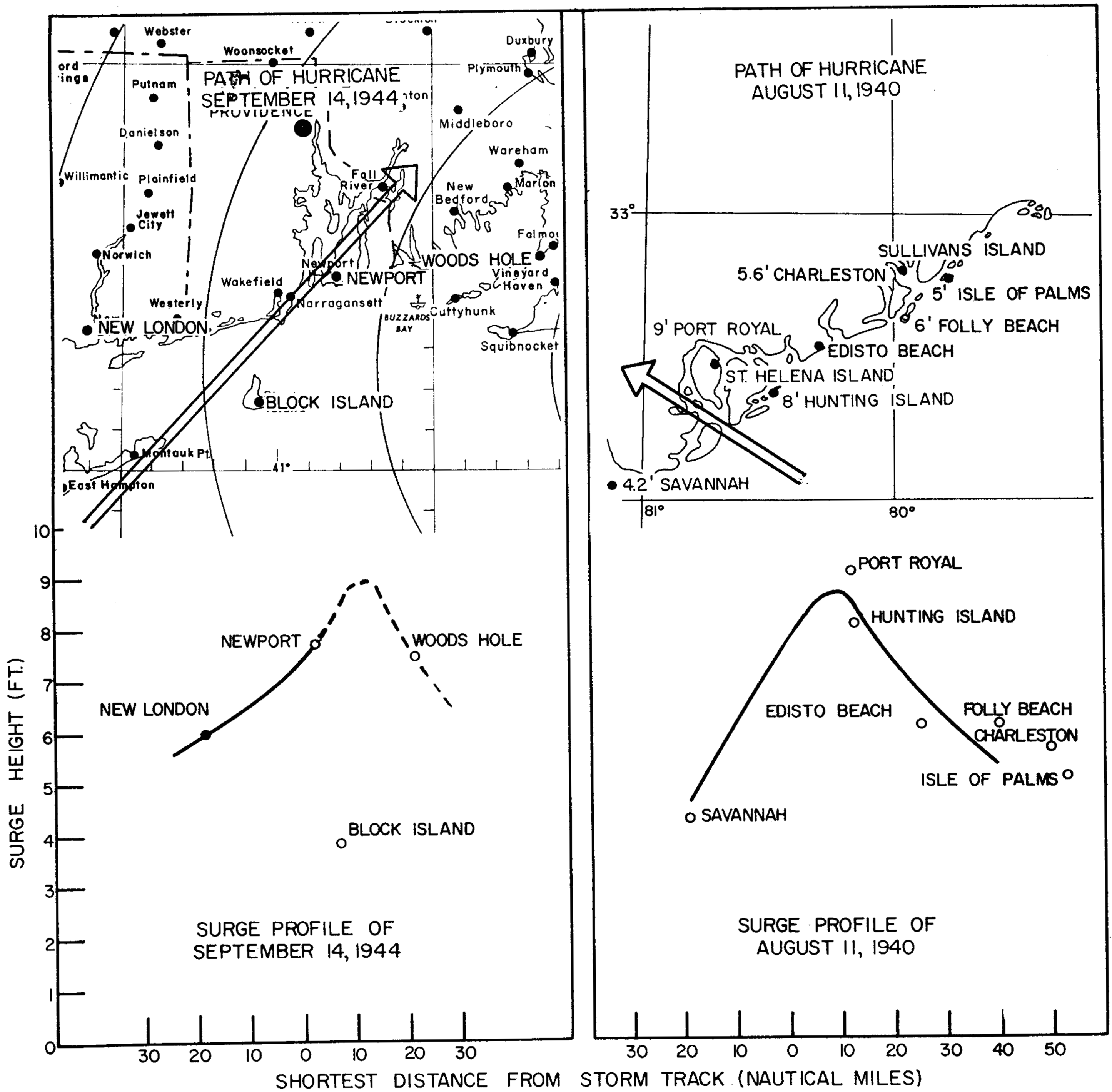

FIGURE 6.—Individual surge profiles for two Atlantic coast hurricanes.

Figure 5 shows the regression of the maximum storm tide height on central pressure for the Gulf storms. The circled numbers indicate heights obtained from the individual tide profiles, while the uncircled ones were estimated from the interpolated and extrapolated profiles.

6. DISCUSSION

The regression line obtained from this sample of Atlantic coast storms may be expressed as

$$h_{ext}=0.198(1006-p_o) \tag{1}$$

where p_o is the central pressure in millibars as the storm came inland and h_{ext} is the extreme storm surge in feet. The coefficient of correlation was found to be 0.86.

The regression line for the Gulf of Mexico coast storms was calculated to be

$$h_{ext}=0.151(1032-p_o) \tag{2}$$

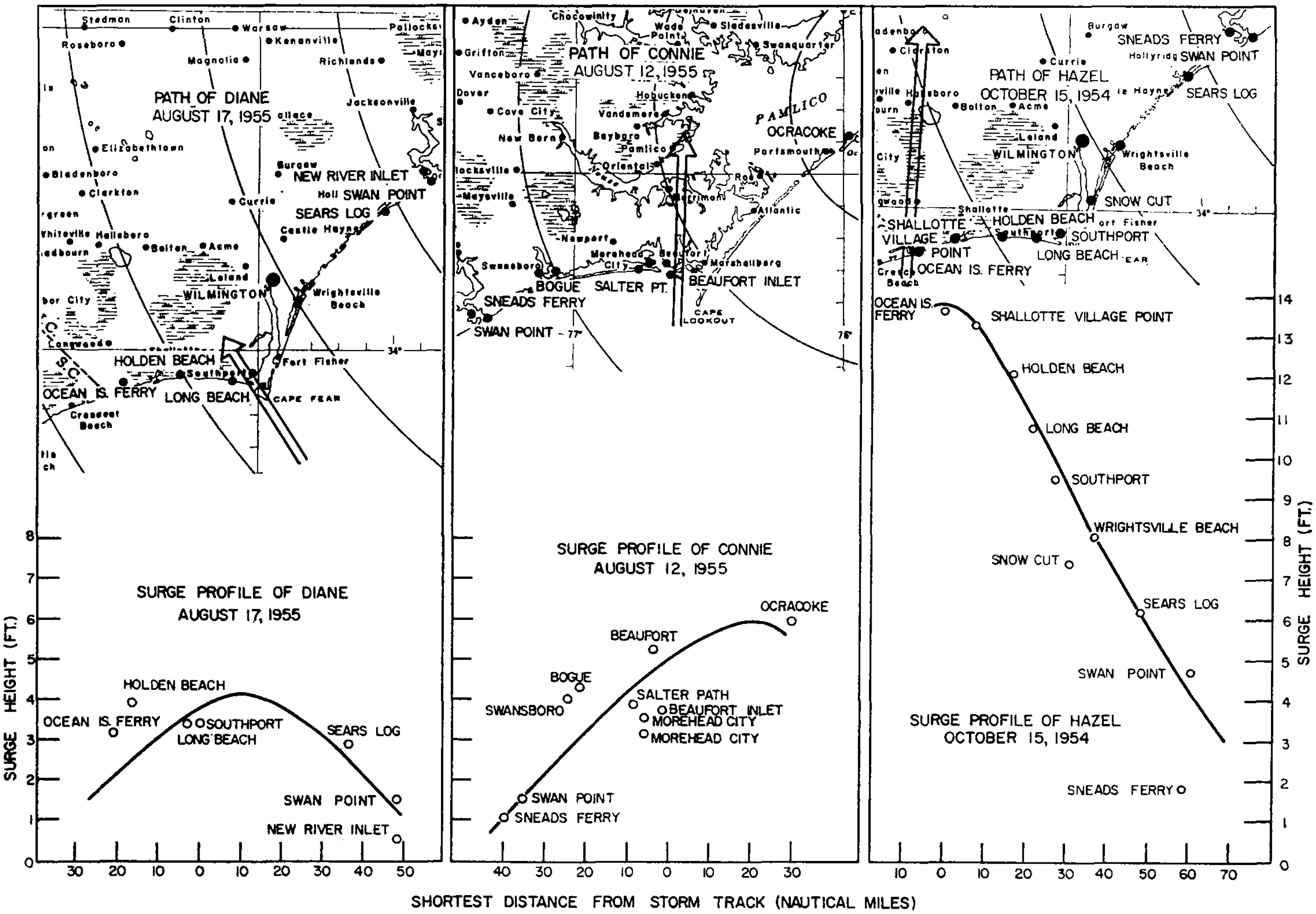

FIGURE 7.—Individual surge profiles for three Atlantic coast hurricanes.

where h_{ext} is the extreme storm tide in feet. The coefficient of correlation here was 0.81.

A test of the statistical significance of the variation in slope between equations (1) and (2), as described by Snedecor [5], indicates that the difference in slope is not significant at the 10 percent level. However, a test of the homogeneity of the entire block of data indicates that the complete equations are significantly different at the 1 percent level. The surges generated by Gulf of Mexico storms appear to be significantly greater than those generated by Atlantic coast storms. No satisfactory explanation for this difference has been found, and additional work on this point is urgently required.

Conner, Kraft, and Harris [1] derive the equation

$$h_{max}=0.154(1019-p_o) \qquad (3)$$

where p_o is the central pressure in millibars as the storm came inland, and h_{max} is the maximum observed value of the storm tide in feet along the Gulf of Mexico coast. The difference in slope between equations (2) and (3) is clearly not significant and the difference in the constant term, amounting to approximately 2 feet in tide height, appears to result from the assumption made in the writer's paper that the actual extreme tide is, in general, higher than the maximum observed tide.

It is believed that the profile technique will prove more valuable in the future study of hurricane surges when some of the uncertainties are removed by the addition of more data.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to the Coast and Geodetic Survey and the U. S. Corps of Engineers for the use of tide data and to Mr. D. Lee Harris for his helpful suggestions.

REFERENCES

1. W. C. Conner, R. H. Kraft, and D. Lee Harris, "Empirical Methods for Forecasting the Maximum Storm Tide Due to Hurricanes and Other Tropical Storms," *Monthly Weather Review*, vol. 85, No. 4, Apr. 1957, pp. 113–116.
2. A. C. Redfield and A. R. Miller, "Memorandum on Water Levels Accompanying Atlantic Coast Hurricanes," Woods Hole Oceanographic Institution, Reference No. 55–28, June 1955.
3. L. F. Hubert and G. B. Clark, *The Hurricane Surge*,

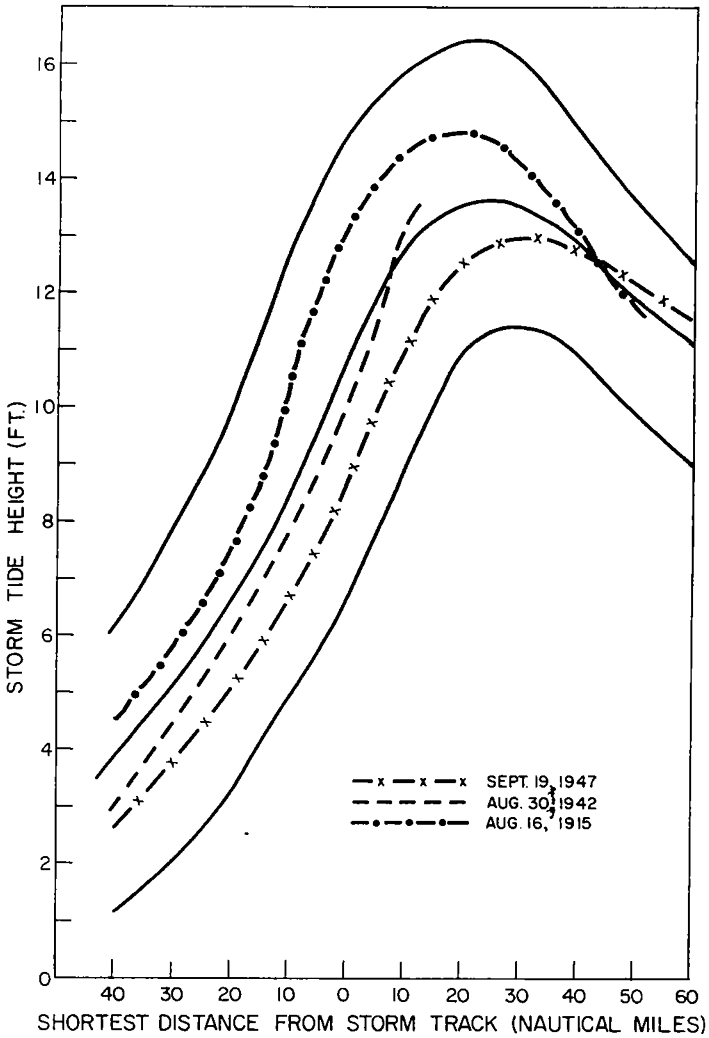

FIGURE 8.—Surge profiles for hurricanes which entered the United States Gulf coastline west of Tallahassee, Fla. from the east-southeast and southeast.

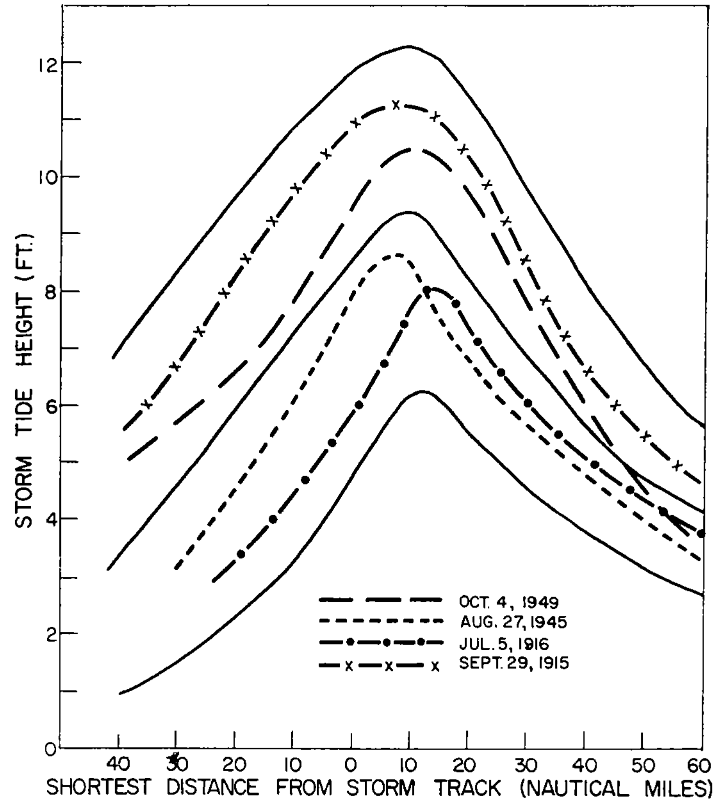

FIGURE 9.—Surge profiles for hurricanes which entered the United States Gulf coastline west of Tallahassee, Fla. from the south-southeast, south, and south-southwest.

an Interim Report, U. S. Weather Bureau, Washington, D. C., June 1955.

4. V. A. Myers, "Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida," U. S. Weather Bureau, *Hydrometeorological Report* No. 32, Washington, D. C., March 1954.
5. G. W. Snedecor, *Statistical Methods*, Iowa State College Press, 3d Ed., 1940, Chap. 12.

APPENDIX

Figures 6 and 7 contain the individual profiles for the balance of the Atlantic coast hurricanes.

Figure 8 contains the profiles for hurricanes entering the Gulf coast west of Tallahassee, Fla., from the east-southeast and southeast. The profile constructed by Hubert and Clark [3] was used for the September 19, 1947 storm. However, some of the tide values from Biloxi, Miss. westward appear to be affected by funnelling and as a result an adjustment was made to the original Hubert and Clark profile. The profile for the August 30, 1942 hurricane was made from tide data supplied by Mr. J. G. Taylor of Galveston, Tex. The following measurements were used: 3.4 ft. at 40 n. mi. to the left of the track, 4.0 ft. at 30 n. mi. to the left, 10 ft. near the center, and 13.8 ft. at 15 n. mi. to the right of the track. The profile drawn by Hubert and Clark for the hurricane of August 16, 1915 was modified somewhat by the addition of tide data supplied by Mr. Taylor.

Figure 9 contains the profiles of hurricanes entering the Gulf coast west of Tallahassee, Fla., from the south-southeast, south, and south-southwest. The profiles of Hubert and Clark were used without alteration for the hurricanes of October 4, 1949 and September 29, 1915. The surge peaks shown by Hubert and Clark for the hurricanes of August 27, 1945 and July 5, 1916 were adjusted slightly to the left to make the curves fit the data a little more closely and to make them more symmetrical.